

Space Communications and Data Systems Technologies for Next Generation Earth Science Measurements

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Prepared for the
Earth Science Technology Conference 2002
sponsored by the NASA Earth Science Technology Office (ESTO)
Pasadena, California, June 11–13, 2002

National Aeronautics and
Space Administration

Glenn Research Center

Acknowledgments

The authors wish to thank the Space Communications and Data Systems program at NASA HQ (formally the Space Operations Management Office at NASA Johnson Space Center) for its ongoing support of the sustaining activities related to these tasks, and the Earth Science Technology Office for its recent support of these tasks.

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Abstract- The next generation of Earth observing satellites and sensor networks will face challenges in supporting robust high rate communications links from the increasingly sophisticated onboard instruments. Emerging applications will need data rates forecast to be in the 100's to 1000's of Mbps. As mission designers seek smaller spacecraft, challenges exist in reducing the size and power requirements while increasing the capacity of the spacecraft's communications technologies. To meet these challenges this work looks at three areas of selected space communications and data services technologies, specifically, in the development of reflectarray antennas, demonstration of space Internet concepts, and measurement of atmospheric propagation effects on Ka-band signal transmitted from LEO.

I. INTRODUCTION

Several technology development tasks being performed at the Glenn Research Center (GRC) and co-sponsored by the Space Communications and Data Systems Project (SCDS) in Code M at NASA Headquarters are being undertaken in support of next generation Earth Science measurements.

Research at GRC in antennas is focused on enabling or enhancing inter-orbital inter-satellite links with government or commercial space networks, intra-network links within science spacecraft constellations, and direct-to-ground links with terrestrial based networks. Advancements in antenna systems technologies increase data return and performance from NASA mission spacecraft while reducing development and operations costs. Electrically steered reflectarray antenna communications systems, based on low-loss ferroelectric materials, are emerging as an attractive alternative to monolithic microwave integrated circuit (MMIC)-based phased array antennas because of the potential for dramatically reduced costs and improved power efficiency. This power efficient Ka-band reflectarray communication system offers the best features of a gimbaled parabolic dish (low cost and high efficiency) and a direct radiating phased array (fast, vibration-free beam steering). It is conceptually depicted in Figure 1. Moreover, the gain of the reflectarray can, in principle, be made as large as desired since there are no power divider losses as in a conventional MMIC-based array. The reflectarray antenna is designed to transmit in the shared government and commercial Ka-band frequency allocation of 25.5 to 27.5 GHz for space science data return links either through TDRS, or direct to the ground. The system can be scaled to other Ka-band frequencies of interest

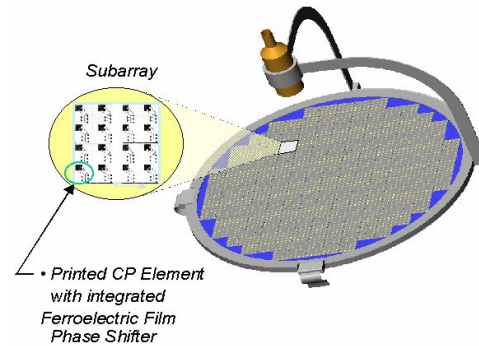


Fig. 1. Reflectarray concept

e.g., 22.55-23.55 GHz for forward intersatellite links. In particular, development of a prototype array controller for the reflectarray antenna will be described for its use in a full scale transmit reflectarray engineering model at 26.5 GHz.

GRC is identifying and enabling the extension of commodity terrestrial-based Internet technologies into future NASA Earth Science missions (e.g., atmospheric, oceanographic, terrestrial). Future mission spacecraft can be compliant with Internet protocols from instrument to investigator, and from mission concept to operations. Critical capabilities enabled by space Internet concepts include establishing network services from unpredictable platform locations at unpredictable times, and maintaining network services while moving from one network to another without any configuration changes or a loss of connection. These capabilities will provide the scientific community with greater control and flexibility over individual experiments and enable new mission concepts and types of science while greatly reducing NASA's cost of providing the communications service. A description will be provided of developing and demonstrating the use of commodity terrestrial Mobile Internet Protocols in dynamic routing environments; investigating the use of network access and control techniques for mobile platforms, and the concept of a spacecraft bus that is compliant from end-to-end with Internet protocols and operational standards.

Ka-Band frequencies, generally between 20–30 GHz, comprise the next higher band of frequencies above Ku-band frequencies that are allocated for broadband global and

domestic fixed- and mobile satellite service. NASA's future data downlink requirements are expected to grow by ten times in future LEO science platforms. The demand for increased bandwidth necessitates the move to higher frequency bands such as Ka-Band. Also, the use of Ka-band frequencies in satellite communications enables a significant reduction in the size and cost of tracking terminal antenna reflectors for comparable data rates in systems operating at X-band frequencies. Future use of new frequency bands demands adequate modeling and characterization of the atmospheric fading effects on the communication channel. An overview is given of the work being done in collecting and analyzing Ka-band propagation data and model development for LEO applications used by NASA, as well as commercial communication system designers.

II. KA-BAND REFLECTARRAY ARRAY CONTROLLER

An electrically steered Ka-band reflectarray based on low-loss ferroelectric materials offers the low cost and high efficiency of a gimbaled parabolic dish, and fast, vibration-free beam steering of a direct radiating phased array. A technology description is provided in [1].

The ferroelectric reflectarray consists of a flat aperture embedded with integral microstrip antenna elements and ferroelectric phase shifters. This surface is illuminated by a single RF source at the resonant frequency of the patch radiators and within the bandwidth of the phase shifters. The energy captured by the patch radiators propagates and returns through the phase shifters and is re-radiated as a collimated beam in any preferred direction. The algorithm to perform beam steering is the same as in a conventional phased array.

Low loss ferroelectric phase shifters being developed in this task enable this revolutionary technology. The design is based on a series of metallic coupled microstrip lines nominally one-quarter wavelength long, patterned on a thin film ferroelectric film (see Fig. 2). A bias of up to 400 V is applied to adjust the relative insertion phase up to 360° . The ferroelectric films are electrical insulators, so current draw, and hence, power dissipation is negligible. Whereas a typical MMIC phase shifter at Ka-band has 8 to 10 dB of insertion loss, the ferroelectric devices have demonstrated 4.5 dB of loss. An insertion loss approaching 3 dB is theoretically possible. Since in the reflectarray configuration the phase shifters are inserted between the amplifier and patch, the insertion loss dominates overall sensitivity (i.e., G/T) in a receive antenna, and power efficiency in a transmit antenna. The smallest feature size of these novel phase shifters is $\approx 10 \mu\text{m}$ compared to $< 1 \mu\text{m}$ for a GaAs MMIC device.

ESTO's investment in a prototype controller for the reflectarray antenna will serve to prove the concept proposed for use in a full scale transmit reflectarray engineering model at 26 GHz. The reflectarray controller will provide a unique

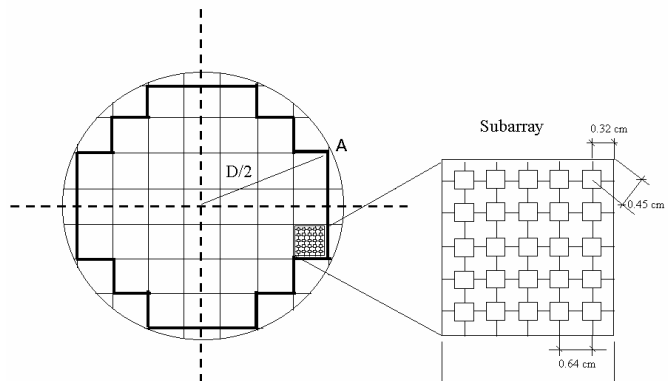


Fig. 2. Reflectarray layout

high-voltage drive signal to each phase shifter in the reflectarray. All phase shifter elements in the reflectarray must be individually biased with a high-voltage signal to obtain the desired antenna beam-scanning angle. Each one of the high-voltage drive signals (616 total) will be independently controlled using a personal computer (PC) connected to the controller and will be adjustable between 0-500 VDC using four (4) bits of resolution (i.e., 31.25 volts per count). In order to provide individual control of all phase shifters, a 10-bit addressing scheme will be implemented to uniquely identify a particular phase shifter within the reflectarray.

Individual phase shifters will be controlled from a parallel digital input/output (I/O) card interfaced to the reflectarray with a 25-pin digital port connector to provide individual control of each phase shifter in the reflectarray. A software application running on the PC will supply the controller with the desired high-voltage value for a particular phase shifter address. Circuitry within the controller will then decode the address and write the high-voltage value to the corresponding phase shifter in the reflectarray. A block diagram of the controller circuitry required for the control of 616 phase shifters is presented in Fig. 3 [2]. As can be seen, the control of a 616-element reflectarray will require a minimum of 616 digital-to-analog (D/A) converters and high-voltage regulators.

The reflectarray controller will have two modes of operation for updating the phase shifters with their corresponding high-voltages values: 1) ripple mode, and 2) parallel mode. In the "ripple" mode, each phase shifter will be updated with a high-voltage value immediately after its address is decoded and the 4-bit high-voltage value is written. The cycle is repeated until all 616-phase shifters in the reflectarray are updated with their new high-voltage values. In the "parallel" mode, a 4-bit high voltage value is written to a phase shifter, but its current high-voltage value is not updated until all 616-phase shifters are written to. Then, a

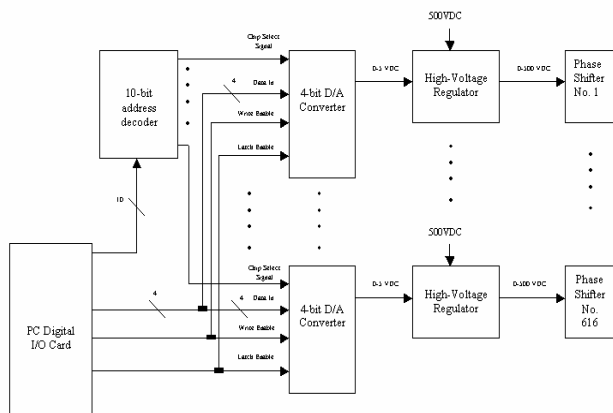


Fig. 3. Reflectarray electrical interface, preliminary design

control signal triggers a simultaneous update of all phase-shifters with their corresponding new high-voltage values. In both modes of operation, a new beam-scanning angle can be selected once all 616-phase shifters have been updated. This updating of the whole array of phase shifters occurs within one second for both the “parallel” and “ripple” modes of operation.

III. IP-COMPLIANT OPERATIONS TECHNOLOGY and DEMOS

Three main areas of ongoing research in Internet protocol (IP) compliant operations and demonstrations are: A) the development and demonstration of the use of commodity terrestrial Mobile Internet Protocols in dynamic routing environments; B) the concept of a spacecraft bus that is end-to-end compliant with Internet protocols and operational standards; and C) investigation into the use of network access and control techniques for mobile platforms. In FY02, ESTO is contributing towards advancements in each of these areas.

Decreasing budgets and increasing demands have placed NASA in a position where data system operations costs must be reduced while overall system loading goes up. The problem is being attacked on several fronts. This task is attempting to leverage the significant commercial investment already made in the terrestrial Internet by applying commercial off-the-shelf (COTS) network hardware and software designs to newly emerging space systems. The new “Space Internet” is expected to save engineering, production, and maintenance costs and will contribute to further cost reduction by developing network enhancements that will enable substantial reductions in real time operations, scheduling, and performance analysis. Development of automated space networks will provide customers direct access to space communications and data services, on a computer-to-computer basis without network personnel intervening. This will reduce the “people in the loop” and the

associated costs thereof. Also, it will reduce the sluggishness that characteristically results when a system is paced by human interfaces. As network performance improves, productivity will improve by utilizing time fragments for active customer support. Once the Space Internet is fully implemented, Enterprise customers will be afforded an entirely new class of service with direct access to their individual space-based experiments and the data generated by those experiments. Annual cost savings through architectural simplification have not been quantified, but are expected to be substantial.

A. Mobile Internet Hardware and Protocol Development

Modern terrestrial Internet systems utilize the Transmission Control Protocol / Internet Protocol (TCP/IP) for the efficient, reliable transfer of commands and data over networks. However, since these protocols were not specifically designed to work in the space environment, further research is needed to identify code enhancements that may be necessary to allow the Space Internet to take full advantage of Internet capabilities. This activity will evaluate COTS hardware and protocols for use in environments with long delays, dynamic path lengths, varying signal strengths, and dynamic routing. It builds on previous activities conducted at both GRC and GSFC. It will also take advantage of collaborative relationships with Cisco (a leading network hardware and software developer), Ball Aerospace (satellite terminals), L3 COM (tracking antennas), US Army Communications Electronics Command (CECOM, developers of secure mobile network systems for the Department of Defense, DoD), US Air Force Space and Missiles System Center (SMC, legacy satellite systems), and the US Coast Guard (USCG, who has provided GRC with a mobile platform for testing). US Army CECOM has also agreed to “sponsor” a National Security Agency (NSA) approved Type I/II encryption device for use with the new mobile router technology. The final product of this activity will be a demonstrated, secure, mobile network that will be ready for qualification and infusion into flight missions. A Cisco mini-router (Fig. 4) is being developed that could enable the first fully IP-compliant mission in space. It will be used to evaluate this concept and demonstrate additional new ideas, such as, the use of true “access on demand” with the



Fig. 4. Cisco mini-router board

Tracking and Data Relay Satellite System network (initially using multiple access, and later using single access service).

B. *IP Compliant Bus*

A companion activity to the development of the mini-router is to develop an IP-compliant satellite bus architecture concept that will be accomplished through a grant to New Mexico State University. This new architecture will show how the mini-router integrates into a satellite bus. The architecture will then be evaluated through a cooperative agreement with Spectrum Astro (a leading spacecraft vendor), currently under contract to NASA Code R's Computing, Information and Communications Technology program for network device development for space. Although a modest activity, this effort is expected to help "bootstrap" the development of future IP-compliant satellite bus architectures in the commercial world as well as gain acceptance by NASA's mission developers.

C. *Remote Spacecraft Access and Control Technique Development*

NASA spacecraft currently require extensive service forecasting and labor-intensive network configuration management whenever they acquire an initial network connection or move between multiple ground stations or space-based communications platforms. Use of Mobile IP will allow widely distributed networks to self-configure for the routing of data and control packets. Central to this activity will be the development of network access and control techniques for mobile platforms with an emphasis on autonomous network scheduling, prioritization, handoffs, and resource allocation management (including link optimization through autonomous spacecraft acquisition and antenna pointing). A demonstration is planned of ground network techniques as a part of the Communications and Network Demonstration on Shuttle (CANDOS) mission onboard the Space Shuttle (STS 107) in July 2002. Also being developed is a secure, autonomous access and control station for future NASA use through a grant with the University of Colorado (for use with the Three Corner satellite) and with a task to contractor Veridian Information Solutions. It may also include collaborative activities with the USAF Tactical Exploitation of National Capabilities program (TENCAP, network security devices) and NSA (penetration testing of the final product).

D. *Related Work*

As has been mentioned, a number of NASA projects, Centers, Government agencies, and civilian corporations are developing IP-related technologies for space (Table 1). This work area builds on their results through collaboration, joint demonstrations, and by synthesizing knowledge gained with them. A number of entities (including GRC) have already demonstrated the use of IP through space (ground-to-space-to-ground) utilizing bent pipe satellite systems (such as

TDRSS, Advanced Communications Technology Satellite (ACTS), and commercial systems). GSFC has demonstrated (in conjunction with the University of Surrey) IP techniques in space utilizing X.25 (amateur radio) protocols. Recognizing the potential of IP in space, this work area intends to leverage significant investment that has already been made in the terrestrial Internet. Collaborative efforts are being leveraged in related areas through relationships with sister Centers (KSC for expendable launch vehicles and JSC for International Space Station), DoD, and commercial industry.

All of the work described in the plan is performed either solely or in collaboration with commercial providers of operational capabilities or universities well recognized by NASA for impartiality and ability to infuse technology into practice. NASA technology development programs typically conclude an activity once it has been demonstrated in the relevant environment. To ensure that the risk is minimized in utilizing these products for future ESE missions, negotiations are underway with NASA Centers, DoD organizations, and commercial entities to incorporate these products into flight opportunities.

TABLE 1
Collaboration

Collaborating Organization	Description
Cisco	Space Act Agreement for prototype satellite routers
Ball Aerospace	Space Act Agreement for prototype satellite terminals
L3 Com	Space Act Agreement for prototype tracking antennas
USCG	Collaborative research on mobile router code, ad hoc networks, and NSA approved encryption devices
US Army CECOM	Collaborative research on mobile router code development, ad hoc networks, and NSA approved encryption devices
USAF/SMC	Collaborative research on the use of IP with legacy satellite systems
DOD/NSA	Collaborative development of IP satellite network architectures
NSA	Collaborative development of IP satellite networks
University of Colorado	Research grant to top academic scholar in the field of remote satellite access control through IP
New Mexico State University	Research grant to top academic scholar in the field of IP-compliant satellite bus design

IV. PROPAGATION MEASUREMENT AND ANALYSIS

The collection and analysis of propagation data and development of models for LEO spacecraft applications at Ka-band will enable communication system designers to improve system availability models used by NASA and commercial mission planners without over-designing the

communication network system link margins. This task builds on propagation work under a previous NASA program, ACTS, the nation's first Ka-band satellite. A very important contribution to the developers of Ka-band satellites has been the multiple site-years of ACTS propagation data and the improvement in models developed by the ACTS Propagation experimenters for satellites in geostationary Earth orbit (GEO). However, NASA's future use of Ka-band for transmission from space to Earth may be greatest in links from spacecraft in low Earth orbit (LEO) where data rates of multiple gigabits per second are forecasted and achievable using Ka-band. But, the atmospheric effects from a LEO spacecraft will vary much more rapidly and significantly than from GEO.

The purpose of the Propagation Measurement and Analysis task is to identify, develop, deploy, demonstrate, evaluate and characterize LEO radio frequency propagation effects and models at Ka-Band frequencies. Most RF propagation effects are considerably more severe at Ka-Band frequencies than at X-band, the frequencies currently used by NASA for space-to-ground links. Propagation data collection and analysis plays a key role in satellite link analysis and future communication component design, capability and requirements. This task characterizes the effects of the Earth's atmosphere on LEO-to-ground Ka-band radio frequency propagation by performing statistical investigations of system availability. It also will lead to improving the system availability models used by NASA mission developers as well as commercial communications system designers without over-designing the communication network link margins.

Currently, there are no LEO attenuation prediction models available to NASA. The LEO propagation work will advance the understanding of the dynamic effects of the Earth's atmosphere on rapidly changing Ka-Band transmission from LEO spacecraft as they traverse the sky. In FY02, ESTO's support will allow NASA to move into this area at Ka-band frequencies. The LEO system that will be used for this task is the Italian Space Agency's Ka-Band DAVID satellite. This task relies on the successful launch and operation of DAVID in April 2004. This system will have a Ka-band beacon signal available at no cost to NASA. NASA costs are further minimized because ACTS propagation terminal hardware will be re-utilized to lower the receive-terminal development. Therefore, funds are needed only for completing ground terminal development, and data collection and analysis. Low-cost commercially available tracking antenna systems will be integrated with commercial receivers, demodulators, and terrestrial interface equipment to provide direct-to-user communications at minimal costs. The first Ka-Band propagation terminal developed is being set-up at the Glenn Research Center (Fig. 5). NASA will further benefit from the sharing of results from its LEO propagation measurement techniques and models with the other



Fig. 5. Prototype LEO Ka-band Propagation Terminal

international community's results involved with DAVID measurements.

Typical NASA missions that can benefit from the broadband capabilities and uncluttered spectrum of the higher bands include advanced science missions in the near-Earth space environment, advanced data relay communications, and deep space and planetary relay communications. Understanding the effects of a dynamic path length and atmospheric constituents on transmissions from LEO spacecraft is extremely critical to the success and efficient operations of future Earth Science missions that will utilize Ka-band communication systems. The Ka-Band propagation measurement and analysis activities described will provide system designers with tools necessary to efficiently design high-speed, wider bandwidth LEO communications "pipelines" that are needed by the Earth Science Enterprise to improve data collection by reducing researchers' access time to data from NASA spacecraft by delivering "fiber-like" signal quality and data rates directly to the user.

V. CONCLUSION

Advancements in antenna technology that provide high efficient, vibration-free, electronically steered beams will enable the Earth Science Enterprise vision for increased data return for direct to ground applications and to interconnect multiple spacecraft, as may be required in a sensor web scenario. The combined reflectarray antenna (funded by Space Communications and Data Systems) and antenna controller (funded by ESTO) is a promising antenna technology to meet ESE's requirements and vision. Combining the efficiencies of the gimbaled dish with the performance and agility of a conventional phased array antenna, the reflectarray antenna, based on a thin film ferroelectric technology, offers a low loss phase shifter coupled with a quasi-optically illuminated, scanning reflector surface to provide a power efficient electronically steered antenna beam. Finally, the reflectarray also offers the potential to reduce manufacturing cost through simple manufacturing processes due to the larger size of the

electronic components and antenna architecture compared to traditional, MMIC-based phased array antennas.

The use of Internet Protocols in space will have profound commercial and societal communication implications. Applying COTS-based protocols and hardware to the Space Internet will be expected to save engineering time and dollars, production and maintenance costs, and will contribute to network enhancements enabling improved real time operations, scheduling and performance analysis. The mobile Internet protocol and key hardware will be evaluated for the long delay, dynamic path lengths, varying signal strengths and dynamic routing needed for space networks. A mobile mini-router being developed by Cisco is one such key piece of hardware. By collaborating with various other interested organizations, the technology can be leveraged and demonstrated to further reduce NASA's risk in infusing this into ESE missions. To ensure a commercial source, the results will continue to be transferred to the private sector for its use in commercial products.

The drive for increased data rates from spacecraft is also driving the need to use Ka-band frequencies in future missions. The greater sensitivity of Ka-band to atmospheric fades mainly due to rain demands that these frequencies are properly characterized and understood especially for the LEO case where space-to-ground path length and properties can vary significantly in a very short time. Utilizing a cost-efficient approach and leveraging past experience from the Ka-band ACTS program, LEO Ka-band propagation measurement and analysis will be performed using an Italian spacecraft, DAVID. Development of the LEO propagation terminal and preparation for this are underway now.

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE October 2003	3. REPORT TYPE AND DATES COVERED Technical Memorandum		
4. TITLE AND SUBTITLE Space Communications and Data Systems Technologies for Next Generation Earth Science Measurements		5. FUNDING NUMBERS WBS-22-258-90-05		
6. AUTHOR(S) Robert A. Bauer, Richard C. Reinhart, Don R. Hilderman, and Phillip E. Paulsen				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration John H. Glenn Research Center at Lewis Field Cleveland, Ohio 44135-3191		8. PERFORMING ORGANIZATION REPORT NUMBER E-14176		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Aeronautics and Space Administration Washington, DC 20546-0001		10. SPONSORING/MONITORING AGENCY REPORT NUMBER NASA TM-2003-212616		
11. SUPPLEMENTARY NOTES Prepared for the Earth Science Technology Conference 2002 sponsored by the NASA Earth Science Technology Office (ESTO), Pasadena, California, June 11-13, 2002. Responsible person, Don R. Hilderman, organization code 6160, 216-433-3538.				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Unclassified - Unlimited Subject Category: 17 Available electronically at http://gltrs.grc.nasa.gov This publication is available from the NASA Center for AeroSpace Information, 301-621-0390.			12b. DISTRIBUTION CODE	
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14. SUBJECT TERMS Atmospheric effects; Satellite communication; Satellite networks; Phased arrays; Protocols; Internets; Reflector antennas; Antenna arrays			15. NUMBER OF PAGES 12	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT	